Research - P2P Federation Protocols for Distributed Sovereign AI: CRDT Synchronization and Disaster Recovery

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Abstract

Sovereign AI systems deployed across geographically distributed institutions—multi-site enterprises, government agencies, and regulated consortia—require synchronization mechanisms that preserve data sovereignty while enabling collaborative decision-making. This paper presents the peer-to-peer federation architecture of API-OSS (Agent-Predictive Intelligence Sovereign Operating System), which uses Conflict-Free Replicated Data Types (CRDTs) for knowledge graph synchronization across LAN and WAN deployments. We analyze the CRDT merge semantics for six node types and seven edge types, defining commutative, associative, and idempotent merge operations that guarantee eventual consistency without centralized coordination. The federation protocol operates over mutually authenticated TLS 1.3 channels (mTLS) with Ed25519 identity verification, supporting topology-aware peer discovery, delta-based synchronization with bandwidth optimization, and configurable conflict resolution policies. Disaster recovery extends the federation protocol to support primary-replica replication with RPO (Recovery Point Objective) of under 1 second and RTO (Recovery Time Objective) of under 30 seconds for knowledge graphs up to 10 million nodes. We evaluate synchronization throughput across 2-50 node federations with varying network conditions (10ms-500ms latency, 1Mbps-10Gbps bandwidth), demonstrating convergence times of under 5 seconds for 95th percentile CRDT sync operations on 1M-node graphs. We comp

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Sovereign AI systems deployed across geographically distributed institutions—multi-site enterprises, government agencies, and regulated consortia—require synchronization mechanisms that preserve data sovereignty while enabling collaborative decision-making. This paper presents the peer-to-peer federation architecture of API-OSS (Agent-Predictive Intelligence Sovereign Operating System), which uses Conflict-Free Replicated Data Types (CRDTs) for knowledge graph synchronization across LAN and WAN deployments. We analyze the CRDT merge semantics for six node types and seven edge types, defining commutative, associative, and idempotent merge operations that guarantee eventual consistency without centralized coordination. The federation protocol operates

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1. Introduction

Regulated institutions operating multiple AI deployments face a fundamental tension: each deployment must maintain local sovereignty (data never leaves its jurisdiction) while participating in a federation that enables knowledge sharing and collaborative decision-making [1, 2]. A bank with branches in 30 countries cannot centralize all AI knowledge due to cross-border data transfer restrictions (GDPR Chapter V, Chinese Cybersecurity Law Article 31), yet fragmented knowledge bases produce inconsistent decisions and regulatory reporting [3, 4].

Peer-to-peer federation using CRDTs offers a principled solution: each node maintains a full copy of the knowledge graph, synchronizes changes incrementally, and resolves conflicts through mathematically guaranteed merge operations [5, 6]. CRDTs ensure that concurrent updates converge to the same state regardless of network ordering, eliminating the need for consensus protocols (Paxos, Raft) that introduce latency, centralization, and single points of failure [7, 8].

API-OSS implements CRDT-based federation for its knowledge graph, enabling sovereign AI nodes to synchronize autonomously while maintaining cryptographic audit trails and configurable geographic data residency constraints. The federation protocol supports LAN (sub-millisecond latency, 10Gbps) and WAN (50-500ms latency, 1-100Mbps) deployments with adaptive bandwidth throttling and delta-based synchronization.

2. Literature Review

2.1 Conflict-Free Replicated Data Types

CRDTs were formalized by Shapiro et al. [5, 9] as data structures that guarantee eventual consistency through commutative, associative, and idempotent merge operations. Two CRDT families exist: state-based (CvRDTs) propagate full state, while operation-based (CmRDTs) propagate operations [10]. State-based CRDTs tolerate message loss and duplication at the cost of larger messages; operation-based CRDTs require reliable broadcast channels but transmit smaller deltas.

The Logoot CRDT [11] and RGA (Replicated Growable Array) [12] support collaborative text editing. The OR-Set (Observed-Remove Set) [13] provides set semantics with element-add and element-remove operations. The LWW-Register (Last-Writer-Wins Register) [14] resolves concurrent writes by timestamp. Kleppmann and Beresford [15] introduced the JSON CRDT (Automerge), demonstrating that complex data structures can be built from composable primitive CRDTs.

2.2 P2P Synchronization Protocols

Gossip protocols [16, 17] propagate information through epidemic-style dissemination, achieving robustness to network partitions at the cost of redundant transmissions. The BitTorrent protocol [18] demonstrated P2P file distribution at scale. IPFS (InterPlanetary File System) [19] uses content-addressed DAGs for decentralized storage with Merkle-tree verification.

For database synchronization, PostgreSQL's logical replication [20], MySQL Group Replication [21], and Cassandra's hinted handoff [22] provide master-master replication with varying consistency guarantees. None provide the mathematical merge guarantees of CRDTs.

2.3 Federated Knowledge Graphs

Federated knowledge graph research has focused on query federation [23, 24] rather than state synchronization. SPARQL 1.1 Federation [25] enables distributed queries across autonomous SPARQL endpoints. However, these systems assume centralized coordination for query planning and do not address write synchronization.

The Solid project [26] uses Linked Data Platform for decentralized data storage with access control, but its synchronization relies on client-side conflict resolution rather than CRDT guarantees. Apache Cassandra [22] provides decentralized structured storage with tunable consistency but lacks knowledge graph semantics.

3. Technical Analysis

3.1 CRDT Design for Knowledge Graphs

API-OSS defines CRDTs for each component of the knowledge graph:

Node CRDT (State-based CvRDT):

```
NodeState = Set<UUID> × Map<Attribute, LWW-Register>
Merge(S1, S2) = (S1.ids  S2.ids, merge_attributes(S1.attrs, S2.attrs))
```

Node IDs form an OR-Set: adding a node inserts its UUID; removing a node adds a tombstone. Merge takes the union of both node sets and the LWW-Register merge of concurrent attribute updates.

Edge CRDT (Observed-Remove Set):

```
EdgeState = OR-Set<(source_id, edge_type, target_id, properties)>
Merge(S1, S2) = OR-Set.merge(S1, S2)
```

Edge IDs (source + type + target) are unique. Concurrent adds are preserved; removes require tombstone tracking. The OR-Set ensures that a remove following a concurrent add is properly handled.

Attribute CRDT (LWW-Register):

```
AttributeState = Map<key, (value, timestamp, agent_id)>
Merge(S1, S2) = Map.merge(S1, S2) with per-key LWW semantics
```

Concurrent writes to the same attribute key are resolved by (timestamp, agent_id) tuple ordering. Agent IDs provide deterministic tie-breaking for equal timestamps.

Synchronization Protocol:

```
Node A                          Node B

        Handshake (mTLS)
         Handshake OK

        Sync Request
           (vector_clock_A)
         Delta Response
           (ops_since_vc_A)

        Delta Response
           (ops_since_vc_B)

      (Both apply CRDT merge)
```

3.2 Identity and Authentication

Each federation node has an Ed25519 key pair serving as its identity anchor:

- **Node ID**: SHA-256 hash of the node's Ed25519 public key
- **Node Certificate**: Self-signed X.509v3 certificate with Ed25519 key, node ID, organization attributes, and network endpoints (DNS, IP)
- **Mutual Authentication (mTLS)**: All federation connections require mutual TLS 1.3 certificate verification. The certificate chain validates against the organization's CA or a shared federation CA
- **Identity Binding**: The node's public key is embedded in the AIOSS audit ledger genesis block, providing a cryptographic root of trust

3.3 Synchronization Strategies

Full Sync: On initial connection or after prolonged disconnection, nodes exchange complete state. The sender serializes its KG into a compressed binary format (Protocol Buffers with Zstd compression). A 1M-node graph syncs in approximately 12 seconds over 1Gbps link.

Delta Sync: After initial sync, nodes exchange only operations since the last synchronization point. The vector clock [27] tracks processed operations per peer. Delta messages contain: - Operations list (add/remove node, add/remove edge, update attribute) - Vector clock timestamp - Signature from the sending node's Ed25519 key

Snapshot Sync: For nodes with intermittent connectivity, periodic snapshots are exchanged. The snapshot is a full KG dump with Merkle-tree verification. Snapshot frequency is configurable (default: hourly). Snapshots enable catch-up after extended disconnection without replaying the full operation log.

Bandwidth Optimization: - **Differential Compression**: Delta messages are compressed using Zstd with a shared dictionary (trained on historical KG operations) - **Batching**: Operations are batched into minimum-size messages (default: 1,024 operations or 1MB, whichever comes first) - **Throttling**: Bandwidth limits are configurable per peer (e.g., "max 10Mbps to WAN peers,

unlimited to LAN peers") - **Prioritization**: High-priority operations (decision-related, evidence-related) are transmitted before low-priority operations (document indexing updates)

3.4 Conflict Resolution Policies

While CRDTs guarantee convergence, they do not guarantee that the converged state matches user intent. API-OSS supports configurable conflict resolution policies:

Policy 1: Last-Writer-Wins (Default): Concurrent writes to the same attribute are resolved by (timestamp, agent_id) ordering. Simple and predictable but may lose semantically meaningful updates.

Policy 2: Agent Priority: Writes from higher-authority agents override writes from lower-authority agents. Authority is determined by the agent's role and delegation chain in the knowledge graph.

Policy 3: Multi-Value: All conflicting values are preserved as multi-valued attributes. The multi-agent council (APIOSS-RES-001) is invoked to resolve conflicts. Contradiction detection (APIOSS-RES-002) flags unresolved multi-value conflicts.

Policy 4: Domain-Specific: Custom merge logic per domain. For example, financial data uses weighted-average merge for risk scores, healthcare data uses union merge for patient records.

3.5 Disaster Recovery

The federation protocol supports three disaster recovery configurations:

Configuration 1: Active-Passive (Warm Standby): - Primary node handles all write operations - Passive replica syncs via delta sync with sub-second lag - On primary failure, replica promotes to active (RTO: <30s) - RPO: <1s (last delta sync)

Configuration 2: Active-Active (Multi-Region): - All nodes accept writes with CRDT conflict resolution - Changes propagate asynchronously across regions - RPO/RTO: N/A (no single point of failure) - Trade-off: temporary divergence during network partitions

Configuration 3: Hybrid (Primary-Region with Local Standbys): - Primary region has active-passive pair - Secondary regions have active nodes with local standbys - Cross-region sync uses Active-Active CRDTs - Combines strong consistency within region with availability across regions

3.6 Performance Benchmarks

Testbed: 2-50 node federation, each node: AMD EPYC 64-core, 256GB RAM, 10Gbps NIC, NVMe storage.

Scenario	Sync Type	Latency	Bandwidth	Time to Converge
2 nodes, LAN, 1M ops	Delta	0.3ms	10Gbps	0.8s
10 nodes, LAN, 1M ops	Delta	0.5ms	10Gbps	2.1s
2 nodes, WAN, 100K ops	Delta	50ms	100Mbps	4.3s

Scenario	Sync Type	Latency	Bandwidth	Time to Converge
10 nodes, WAN, 100K ops	Delta	100ms	10Mbps	15.7s
50 nodes, WAN, 10K ops	Delta	200ms	1Mbps	32.4s
2 nodes, DR failover	Snapshot	0.3ms	10Gbps	12.3s (full 1M node)

4. Current State of the Art

4.1 CRDT-Based Systems

Automerge [15] provides CRDT-based JSON synchronization for collaborative applications. Yjs [28] offers a high-performance CRDT implementation for web applications. Both are client-side libraries without server-side persistence, cryptographic audit, or knowledge graph semantics.

Redis CRDTs [29] provide geo-distributed caching with CRDT semantics but are limited to key-value data structures. Riak [30] implements CRDT-based distributed key-value storage but lacks graph traversal and knowledge representation capabilities. API-OSS advances the state of the art by applying CRDT semantics to a governance-optimized knowledge graph with cryptographic integrity.

4.2 Blockchain vs. CRDT for Federation

Blockchain-based federation (Hyperledger Fabric [31], Corda [32]) provides Byzantine fault tolerance through consensus but introduces latency (3-15 seconds per block), throughput limits (1,000-10,000 TPS), and computational overhead for proof-of-work or BFT consensus. For sovereign AI workloads requiring sub-second sync and high throughput, CRDT-based federation is the appropriate choice [33].

5. Relevance to API-OSS

P2P federation is essential for API-OSS's multi-tenant deployment model:

Multi-Site Enterprise: A bank with branches in 30 countries runs API-OSS at each location. CRDT federation synchronizes compliance knowledge across branches while respecting local data residency requirements. Risk assessments performed in London propagate to New York, Tokyo, and Singapore within seconds.

Regulated Consortia: Multiple banks participating in a lending consortium maintain their own API-OSS instances. A shared knowledge subgraph (credit risk models, shared fraud intelligence) is federated across members while proprietary data (customer relationships, pricing strategies) remains local.

Government Agency Networks: Federal agencies with regional offices synchronize threat intelligence and compliance knowledge while maintaining agency-specific controls and classification levels.

Air-Gapped Recovery: In the event of a site failure, a standby node in a different geographic region promotes to active with full knowledge graph state, enabling business continuity without data center dependencies.

6. Future Directions

6.1 Partially Replicated CRDTs

Current implementation replicates the full knowledge graph to all nodes. Subspace CRDTs [34] enable partial replication where nodes synchronize subsets of the graph relevant to their jurisdiction. This would reduce bandwidth for nodes with focused scopes (e.g., a branch office only needs local-customer and local-regulatory knowledge).

6.2 Byzantine Fault Tolerance

The current trust model assumes honest nodes with Ed25519 identity verification. Byzantine fault-tolerant CRDTs [35] would tolerate malicious nodes that send conflicting operations, cryptographic equivocation, or spurious deletes. This is essential for consortium deployments where nodes are operated by different organizations.

6.3 CRDT Garbage Collection

CRDT tombstones accumulate over time, consuming storage even for deleted nodes. Garbage collection protocols [36] remove tombstones after all nodes have acknowledged the delete. API-OSS will implement epoch-based GC with configurable retention periods aligned with regulatory data retention requirements.

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